A VERSATILE VANE-SHEAR APPARATUS

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THESIS

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ABSTRACT

The vane-shear devices currently in use exhibit inherent problems and shortcomings associated with their design. The PGS Vane-Shear Apparatus is designed to eliminate these shortcomings. The unique features of the device include:

a. Ability to be used in the laboratory or on board a ship.

b. A single unit which is easily calibrated and capable of measuring torque over the entire range commonly encountered in marine sediments.

c. A torque transducer which is insensitive to temperature changes and orientation.

d. Ability to determine shear strength prior to cutting the core liner, thus reducing the disturbance to the sediment caused by cutting and handling.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

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INTRODUCTION

Recent years have seen a growing interest by both private industry and government agencies in the physical characteristics of the marine sediments on the continental shelf and the deep sea floor. Extensive efforts are being expended to determine such factors as:

a. The amount of support sea floor sediments can provide objects placed on the bottom, such as platforms, instruments, and manned habitats.

b. The breakout forces required for large-object salvage operations.

c. The degree of trafficability of the sea floor.

d. Ability of slopes on the sea floor to resist sliding.

All of these factors are directly or indirectly related to the shear strength of the sediment. It can be demonstrated that the shear strength of a marine sediment can be expressed by Coulomb's formula:

$$s = c + N \tan \phi$$

where s = total shear strength

c = cohesion

N = effective normal stress

ϕ = angle of internal friction.

The significance of each of these terms are discussed in the standard texts on soil mechanics. Fine-grained, saturated marine sediments stressed without loss of pore water are generally assumed to behave as if they were cohesive materials without any internal friction under normal loading. For these conditions the angle of

internal friction will be equal to zero [Keller, 1968]. The shear strength of saturated marine sediments is therefore sometimes alternately referred to strictly as cohesion. Measurement of the shear strength of marine sediments may be made by direct shear, triaxial shear, and unconfined compression tests. These tests require the sample to be removed from core liners, and the resulting disturbances may appreciably affect the results of the tests. These shortcomings can be minimized by applying the vane shear test [Smith, 1962].

All vane shear testing devices currently in use are adaptations of the vane borer, which was developed simultaneously in Sweden by John Olsson in 1928 and in Germany as evidenced by a patent in 1929 [Osterberg, 1957]. These devices received little attention until Cadling and Odenstad [1950] reported results of comprehensive tests conducted in Sweden on the shear strength of clays. This report described a method of obtaining shear strength of clays in-situ. The equipment used by them consisted of four rectangular shaped vanes, welded at right angles to a rod. The vane assemblage was inserted into a hole bored into the ground and extensions added to the rod until the vane reached the bottom. The vane was then driven into the undisturbed soil below the bore hole and torque applied to the rod from the surface. This torque was measured by means of a calibrated spring. The vane was rotated until the maximum torque was reached, followed by a decrease to a value which was necessary to maintain a constant rate of rotation of the vane. The shear strength of the soil was then determined from the following equation, which was derived by Cadling and Odenstad:

$$s = \frac{M_{max}}{\left(\pi\, DH \frac{D}{2} + 2 \frac{\pi D^2}{4} \frac{2}{3} \frac{D}{2}\right)}$$

where M_{max} = maximum torsional moment required to produce shear

D = diameter of the vane

H = height of the vane.

The above equation assumes the surface of rupture is a circular cylinder surrounding the vane, with the height and diameter of the cylinder being equal to the dimension of the vane. It is also assumed the stress distribution at the maximum torsional moment is uniform across the surface of the cylinder including the end surfaces. The friction exerted by the soil on the shaft of the vane is considered negligible. These assumptions are taken to be valid in all vane shear testing devices currently employed.

Cadling and Odenstad also report that the rate of rotation of the vane influences the results, with a higher shear strength being associated with the higher rotation rate. They worked with rotation rates from 0.1 to 1.0 degrees per second and note that higher rotation rates may yield shear strengths as much as fifteen percent greater than the shear strength determinations at the lower rotation rate. On the assumption that the reported values of shear strength should correspond to the most unfavorable case, the rotation rate of 0.1 degrees per second was adopted as standard. Various investigators have abandoned this "standard" in favor of higher rotation rates. Morelock [1967] uses a rotation rate of 0.2 degrees per second, assuming that the resultant increase in shear strength is minimal and that the higher rate is much more practical when examining large

numbers of samples. Bouma, Bryant, and Tieh [1968] have apparently used the 0.2 degrees per second rotation rate in their studies of the continental shelf of the Gulf of Mexico. Aas [1965] reports finding no significant difference in shear strength by using rotation rates from one to ten revolutions per hour and all intermediate values.

The height/diameter (H/D) ratio of the vanes has been studied extensively by Cadling and Odenstad [1950], who use an H/D ratio of two as the standard for their work. Aas [1965] experimented with various vane shapes to determine whether the H/D ratio significantly altered the test results, and concluded the results were not appreciably changed unless the H/D ratio was greater than three. Osterberg [1957] suggests that to avoid disturbance of the soil to be tested, the area of the vane should not exceed 10 percent of the area of the circular section to be sheared.

The vane borer of Cadling and Odenstad was the predecessor to all vane-shear devices currently used in determination of the shear strength of marine sediments. While it was designed for testing terrestial soils, those subsequently developed for testing marine sediments are scaled-down models of the vane borer. Although the principles remain the same, the shear strength, torsional moments measured, and the dimensions of the vanes are several orders of magnitude less when dealing with marine soils.

The following comparison illustrates the differences between terrestial and marine soils:

Typical Marine Sediments, West Coast of North America [Moore, 1961]

	Shear Strength (gm/cm^2)
Open continental shelf	11
Continental borderland, basins, and slopes	18
Bays and estuaries	13
Continental slope	7
Deep-sea terregenous	26

Classification of Terrestial Clays [Terzaghi and Peck, 1948]

Term	Shear Strength (gm/cm^2)
Very soft	< 250
Soft	250 -- 500
Firm	500 -- 1000
Stiff	1000 -- 2000
Very stiff	2000 -- 4000
Hard	> 4000

It can be seen from the comparison above that any device which is to be used on marine sediments must be capable of measuring comparatively low values of shear strength.

EXISTING EQUIPMENT

There are several variations of vane-shear testing equipment currently used to determine the shear strength of marine soils. The devices most widely used or those with particularly interesting features are mentioned below.

The Wykeham Farrance Vane-Shear Apparatus

The Wykeham Farrance Vane-Shear Apparatus (Figure 1) is manufactured in England and is in wide use throughout the world. It is available in two versions: the hand-driven model, in which the vane is rotated by manually turning a hand crank, or the motor-driven model. Several vane rotation rates are available, with 6^{o} per minute the standard equipment.

The sample container is secured to the base plate to prevent its rotation during the test. The vane is lowered into the sample by means of the top hand crank until the top of the vane is at least 0.75 inches below the surface of the sample. The torque necessary to shear the sample is measured by a spring having a linear response to torque. The spring is calibrated by the manufacturer, who provides the linear spring constant associated with each spring. Two dials are provided on the upper part of the apparatus. The outer dial indicates the degrees of rotation of the vane, while the inner dial shows the degrees of applied torque. The outer and inner dials are initially set to zero, and the test is started by turning on the motor or by manually turning the side hand crank. When the sample shears, the vane rotates at the same speed as the application of torque. The inner dial will remain on the reading at the time of shear, while the outer dial continues to rotate until the

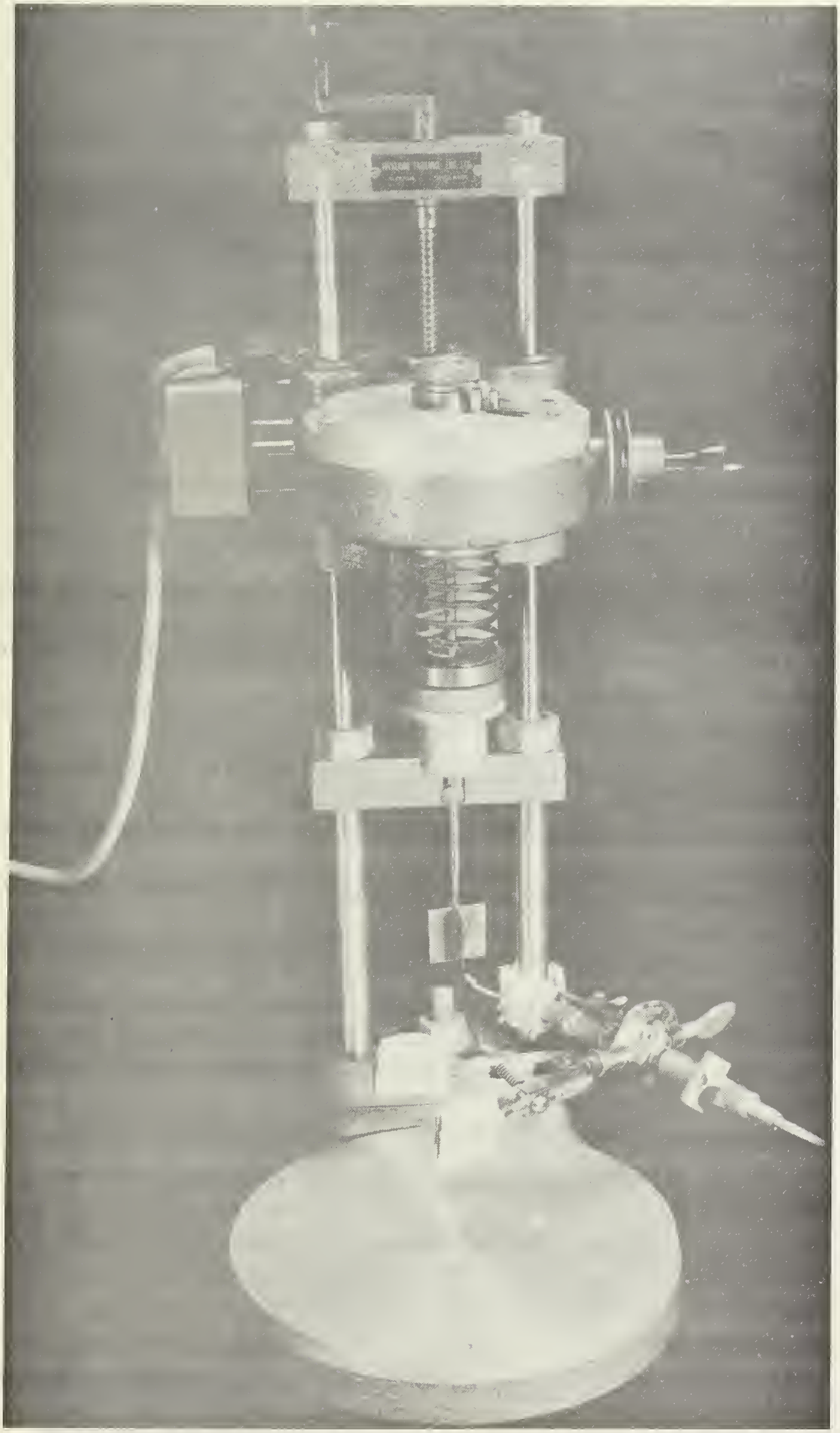

Figure 1. The Wykeham Farrance Vane-Shear Apparatus

motor is turned off or the cranking stopped. The amount of torque necessary to shear the sample is determined by dividing the reading on the inner dial at the time of shear (applied degrees of torque) by the spring constant. The shear strength is then determined by:

$$s = \frac{\text{torque}}{2\pi r^2 (h + 0.667r)}$$

where h = height of the vane

r = radius of the vane.

According to Richards [1961], a vane rotation of at least 20 degrees is required for a valid test.

The Wykeham Farrance apparatus apparently yields good results, although very sensitive springs are required for soft soils which shear at the very low torque ranges. In addition, the spring calibration must be checked frequently to ensure the spring has not been stretched beyond its elastic limit. The principal advantages of the Wykeham Farrance apparatus are that it is simple to operate, is relatively light-weight, and can be used aboard ship or in the laboratory. The primary disadvantages are that it does not provide a continuous and permanent record of the soil shear, and spring calibration must be checked frequently. To obtain a sequential record of a test, it is necessary for the operator to record the degrees of applied torque every 2^{o} of vane rotation during the test. The values must then be plotted, a process which is not difficult but exceedingly time consuming. In addition, much of the detail of the shear profile is lost by manual plotting.

NCEL Vane-Shear Apparatus

The NCEL vane-shear device shown in Figure 2 was designed by Smith [1962] at the Naval Civil Engineering Laboratory, to provide a high

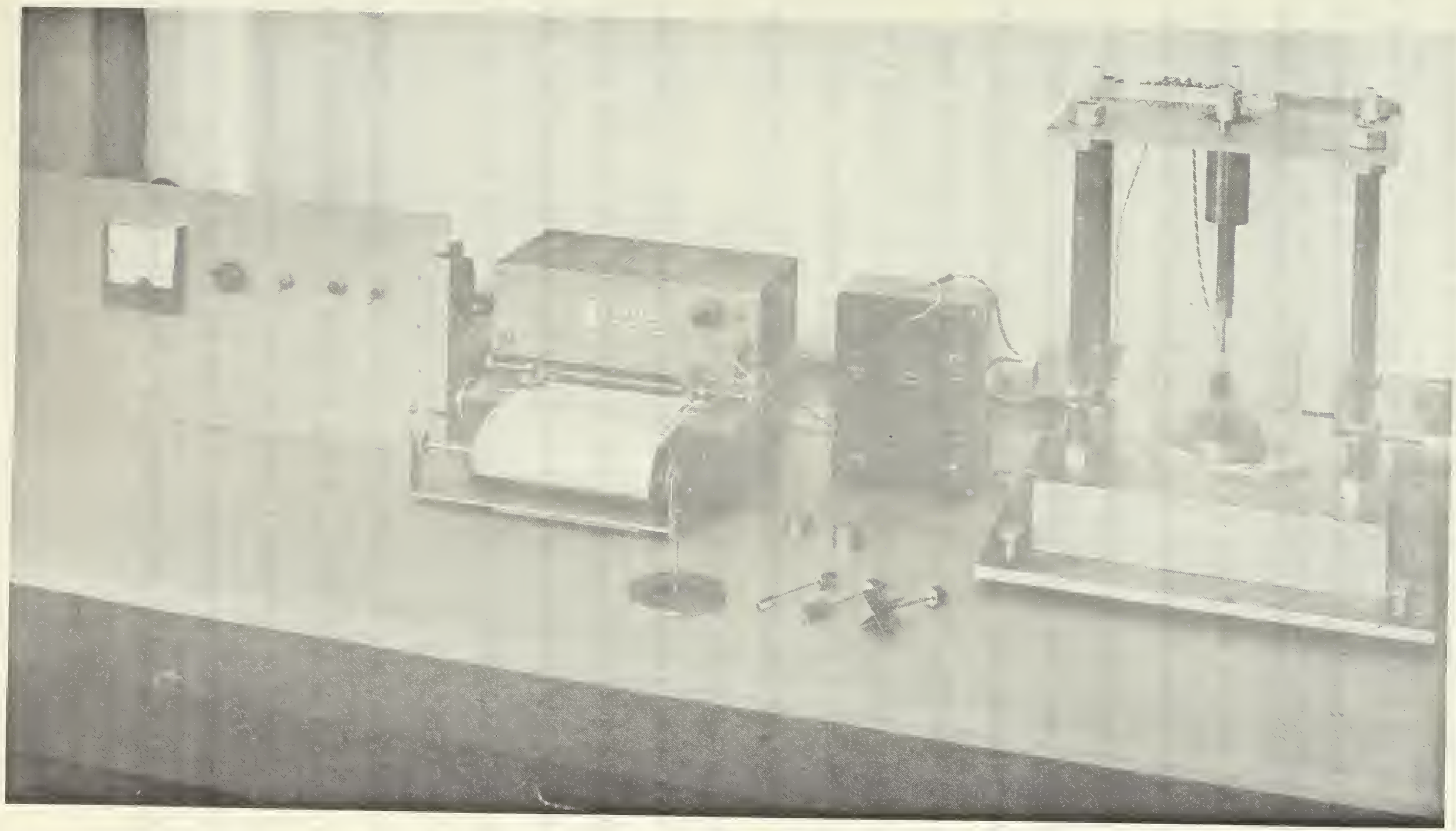

Figure 2. The NCEL Vane-Shear Device

degree of sensitivity throughout the range of shear strengths normally encountered in marine soils, while allowing a continuous and permanent record of the test. The sample to be tested need not be removed from the core liner, as the liner segment containing the soil is fastened to a disc which is rotated by a motor mounted beneath the base plate. The vane remains fixed throughout the test while the sample rotates around the vane. The vane is attached to a shaft, which in turn is guided through an upper plate by means of a teflon bushing and ball bearings.

The top of the shaft is equipped with cantilevered feeler gauge stock reeds equipped with SR-4 strain gages. The ends of the reeds rest against vertical posts attached to the upper plate assembly. As the sample is rotated, torque is applied to the shaft which in turn bends the reeds. The strain gages, in turn, measure the distortion of the reeds which is proportional to the torque developed. Interchangeable reeds, having thicknesses of 1/64 and 1/32 in. are provided to allow for variability in the samples being tested.

Power to the strain gages and the bridge balance unit is provided by rectified 110 volt a-c source. The imbalance of the bridge caused by the output of the strain gages is amplified, and the output is fed to a strip chart recorder. Thus, a permanent record of the entire test is available.

The apparatus is easily calibrated by use of a calibration wheel which is screwed into the shaft. Known weights are passed over a guide block while attached to notches in the calibration wheel. In this manner, known torsional moments are utilized to adjust the amplifier gain to the desired level. Calibration can be accomplished in five minutes.

The NCEL Vane-Shear Apparatus is restricted to laboratory use only, and cannot be used aboard ship. The unit must be precisely leveled on the laboratory work bench to prevent misalignment of the shaft, and attendant binding in the bushing and ball bearings. Binding occurs if the shaft is not maintained exactly vertical. The shaft configuration is such that samples in excess of 3 inches in length cannot be tested.

IIT Vane-Shear Test Apparatus

An interesting apparatus designed to measure vane-shear strength with the soil sample under high environmental pressures, and patterned after the NCEL vane-shear device, was developed at the Illinois Institute of Technology (IIT) Research Institute by Vey and Nelson [1966].

The soil specimen is placed in a 2.5 x 2.0 inch container fitted with a porous stone at the bottom to provide drainage. The vane, shaft, and transducer assembly are then mounted to the top cover of a pressure vessel. The torque transducer consists of a beam rigidly mounted to the shaft. A rigid post mounted 2.0 inches from the center of the shaft keeps the beam from rotating, thereby providing the bending moment to the beam. SR-4 strain gages attached to both sides of the beam then measure the deflection due to twist from the shaft.

The torque transducer is contained in a plexiglass housing filled with oil and has a flexible diaphragm cover to equalize the fluid pressure in the housing.

Calibration of the torque transducer while under pressure is accomplished by mounting a calibration wheel to the shaft. A known torsional moment is applied to the shaft via the calibration wheel by means of weights attached to a cable. A small weight is always suspended

from the calibration wheel. This ensures that the beam is in contact with the rigid post support at the start of the test.

The entire vane-shear apparatus, including the soil sample, is placed in a pressure chamber by securing the top cover to the pressure vessel. Vane shear tests may be conducted at environmental pressures from atmospheric to 5000 psi and at temperatures from $1^{o}C$ to $3^{o}C$.

Diver-held Vane-Shear Apparatus

An inexpensive diver-held vane-shear apparatus capable of in-situ operation in shallow waters has been developed by Dill and Moore [1965]. The device consists of a commercial torque screwdriver with a 3/4 x 3/4 inch vane attached to the shaft. The device is capable of measuring torques from 0-24 inch-ounces. According to Moore [1962], these parameters (3/4 in x 3/4 in vane, 0-24 inch-ounces torque) are adequate for most shear strengths encountered in the upper six inches of marine sediment.

The device has proven useful in determining shear strength and residual strength in and around an active slumping area at the head of Scripps Submarine Canyon. It has also been used successfully on board ship to determine shear strength of relatively undisturbed sea-floor sediments obtained by box samplers.

The primary disadvantage of a device of this nature is that there is no means of controlling the rate of stress application. In this instance the diver was instructed to gradually build up torque over a period of not less than two minutes, until the sediment sheared. It is difficult, if not impossible, for a diver to duplicate the rate of stress application. Another disadvantage is that the shear pattern cannot be

obtained since no permanent record is made. It may be desirable to forsake this record for an in-situ test, but for shipboard and laboratory vane-shear tests, a permanent record is highly desirable.

DESIGN CONSIDERATIONS

The following presents some of the more important factors which must be considered in designing a vane-shear apparatus. These factors explain, in part, the final design and component selection of the items that constitute the vane-shear apparatus described in the following chapter.

General

A vane-shear apparatus should be versatile, performing equally well aboard a vessel at sea or in the laboratory. In order to meet this criteria, the device must be capable of being easily assembled and/or disassembled, portable, preferably light-weight, and with no special leveling required. At the same time, the individual components must be sturdy enough to withstand the inevitable jolts incurred during transportation.

Vane shear tests are generally conducted on soils contained in a core segment which has been cut from the core liner. It would be more desirable to conduct vane shear tests on a soil prior to cutting the core liner into segments in order to minimize disturbance. The vane-shear test could be run on the uppermost portion of the core. The core liner could then be cut and the vane-shear test is run on the next section while still intact with the remainder of the core. This procedure would minimize disturbance of the sediment sample. When the core is cut into sections prior to testing, each section is subjected to two cuttings except for the top and bottom segment of the core.

Torque Measurement

The critical component of any vane-shear device is that part which measures the amount of torque on the vanes at the time the soil shears. Regardless of the type of device used to measure torque, it must be capable of measuring the entire range encountered in the determination of shear strength of marine soils. Table I shows the range of shear strengths commonly found in marine soils. Table II shows the torque required to produce the shear strength reported in Table I. Examination of these tables reveals that by proper choice of the vane size, a device capable of accurately measuring 1-250 inch-ounces of torque is adequate except in the most unusual circumstances. Measurements of torque in the higher ranges present no special difficulty, but a very sensitive instrument is required to measure torque in the neighborhood of 1 inch-ounce or less. Sensitive, calibrated springs are easily damaged by straining beyond their elastic limit. The use of electronic, strain-gage transducers is feasible but presents problems of signal discrimination over noise at these low torque values.

It is highly desirable to utilize a single unit, rather than interchangeable units which cover only discrete segments of the torque range. Such a single unit eliminates errors in judgment on the operators part, and thus saves time and produces more accurate results. Once a sepcific area of a soil sample has been sheared, it is impossible to obtain an accurate value of shear strength at the same location on a test re-run.

Power

If electronic devices are to be used in the apparatus, provision should be made for a regulated power supply. Voltage and frequency

TABLE I

Ranges of Shear Strengths[1]

	NCEL	RICHARDS	HAMILTON & MOORE	NCEL	HAMILTON	HORN AND LAMB
Number of cores tested	39	31	10	75	--	7
Number of tests per core	1-15	1-34	1-4	1-21	--	1-12
Sample depth (m)	Surface	Surface	0-168	Surface	Surface	10-25
Shear strength (gm/cm^2)	1.2-138	4.0-234	610-8000	1.5-380	4.0-192	75-1200

TABLE II

Torque Required to Produce Shear (inch-ounces)[2]

1/2" x 1/2" vane	.070-8.2	.24-13.9	36.3-476	.09-22.6	.24-11.4	4.5-71.5
1" x 1/2" vane	.12-14.4	.35-24.4	63.6-834	.16-39.6	.42-20.0	7.8-125
1" x 1" vane	.57-65.8	1.9-111	290.8-3814	.72-180	1.9-91.6	35.8-572
2" x 1" vane	1.0-115	3.3-195	590-6675	1.3-319	3.3-160	62.6-1001

[1]Tables compiled by H. Herrmann [1966].

[2]Torque calculations are the responsibility of the author. Columns correspond to those of Table I.

surges are common in electrical circuits, both in the laboratory and aboard ship. Surges of this nature can produce erroneous signals in sensitive electronic equipment. Whenever possible, circuits provided with stabilizing transformers should be used. (Such circuits are not commonly found aboard ship.)

The basic power supply should be 115 volt-60 cycle, enabling the unit to be used anywhere.

Recording of Test Results

The desirability of a continuous graph-type record of the test has been emphasized throughout this study. Such a graph provides a shear profile, which varies with different soil types. These profiles may be obtained by manually plotting torque versus degrees of vane rotation at discrete points throughout the test but are demanding upon the time of the laboratory technicians, especially when a large number of tests are to be conducted. In addition, minute variations in the shear profile are missed by incremental plotting.

Motor

The ideal motor for rotating the vanes or the sample is one which is variable in speed, can provide the necessary torque, and does not require gear reduction to produce the desired rotation rate. Unfortunately, such motors are not available. The slow rotation rates commonly employed (1-2 revolutions per hour), coupled with the torque requirements, are too demanding upon the armature of the motor. Consequently, reduction gears must be relied upon to produce the desired rotation rate. Every attempt should be made to use precision gearing in order to eliminate "slop" and the attendant vibrations. Vibrations of this

nature can be transmitted through the vanes or sample holder (depending upon whether the vane or the sample is rotated) to the test specimen, resulting in undue disturbance.

Variable speed motors should be avoided because of their tendency to "hunt" under changing torque loads.

<u>Sample Holders</u>

Care must be exercised in the design of sample holders to avoid stress application to the sample. Compressive forces on the side walls of the core liner or sample container should be avoided. Such compressive forces result in soil disturbance and erroneous results. Where possible, the forces necessary to prevent the sample from rotating during the test should be exerted on the core liner in a vertical direction.

If the vane-shear tests are to be conducted prior to cutting the core liner, as explained in the general discussion section of this chapter, the sample holder should maintain the core as nearly vertical as possible to prevent excess water drainage and separation of the soil from the walls of the core liner.

THE PGS VANE-SHEAR APPARATUS

The design of the vane-shear device was selected following a review of the literature, conversations with users of the various existing vane-shear devices, and correspondence with numerous manufacturers of component parts.

General Description

The PGS vane-shear apparatus may be configured for laboratory or shipboard use. The combined weight of all the component parts (less recorder) in the laboratory configuration shown by Figure 3 is 26 pounds, and the total weight in the shipboard configuration of Figure 4 is 44 pounds.

The PGS vane-shear apparatus consists of the following components:

1. torque transducer
2. power supply and signal conditioning unit
3. bracket arm
4. swivel assembly
5. rack and pinion assembly
6. motor and motor mount
7. calibration stand and wheel.

All components except the torque transducer, power supply and signal conditioning unit, and the recorder were constructed by the Machine Facility at the Naval Postgraduate School during December 1969 and January 1970. A description of these parts is contained in the following sections.

Torque Transducer

A review of various torque measuring techniques indicated the desirability of utilizing a torque transducer in this apparatus. This

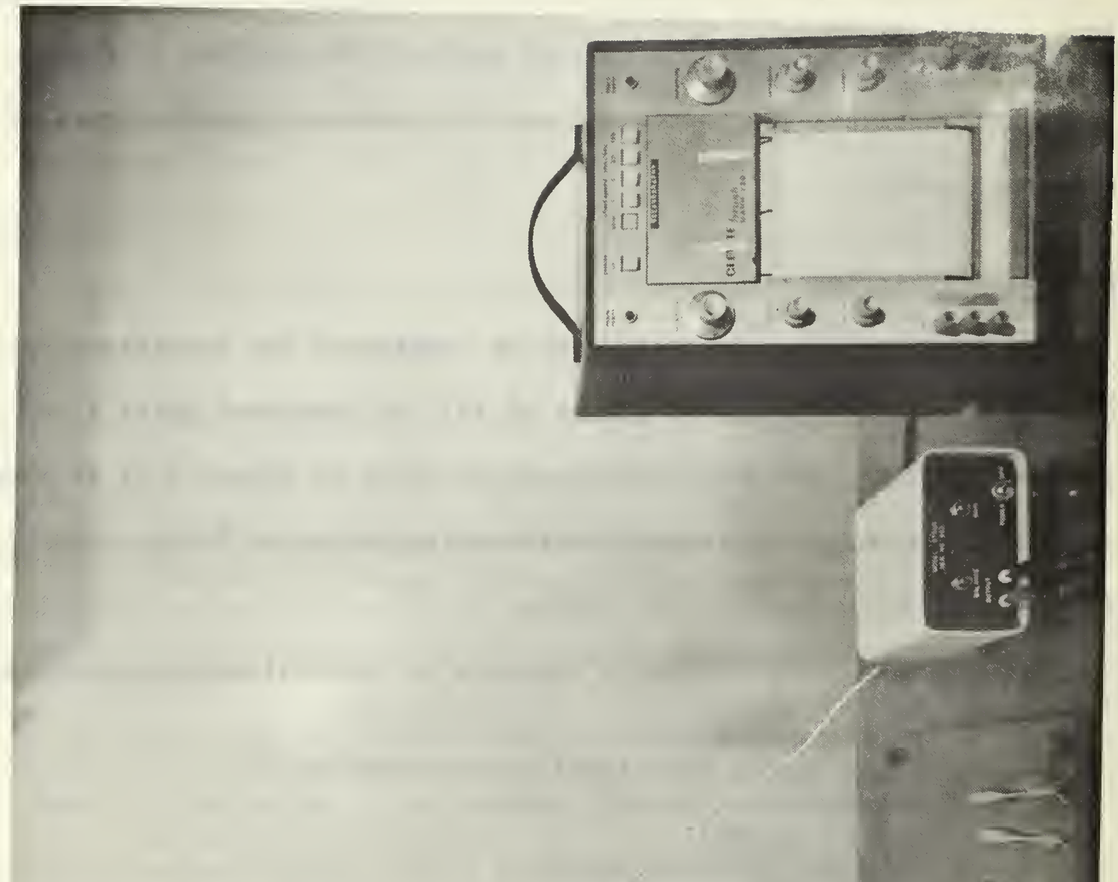

Figure 3. The PGS Vane-Shear Apparatus, shown in the Laboratory Configuration

Figure 4. The PGS Vane-Shear Apparatus, shown in the Shipboard Configuration

eliminates many of the disadvantages of the calibrated spring. The torque transducer selected, as shown in Figure 5, is an in-line, semiconductor strain gage transducer, Model A44, manufactured by West Coast Research Corporation of Santa Monica, California. The range of the transducer is 0-250 inch-ounces, although it may be over-torqued 100 percent without damage. The output of the transducer is .269 millivolts/volt excitation/inch-ounce, and is linear throughout the entire range. Accuracy of the torque measurement is $\pm$ 0.1 percent throughout the range. The internal resistance of the transducer is 350 ohms. For all practical purposes, it is insensitive to temperature change with a temperature response of 0.0045 millivolts/degree Farenheit, and 72°F being the calibration temperature. The transducer will measure either clockwise or counterclockwise torque, the polarity of the output signal indicating the direction.

The semiconductor type transducer was used because of its ability to discriminate signals over noise in the very low torque ranges. The use of semiconductors enhances signal discrimination at these low output levels by a factor of approximately thirty over the conventional strain gage. Excitation to the strain gages is a regulated 5 volt DC signal from the power supply unit. Because of the slow rotation rate involved, slip rings are not needed, which helps to eliminate noise in the output signal. The output is unaffected by the orientation; it may be used horizontally, vertically, or in an oblique attitude.

The top of the transducer is provided with a 1/2 inch long 1/4"-28 thread stud which is screwed into an adapter when the transducer is used for testing. When calibrating the equipment, this stud screws into the

Figure 5. The Torque Transducer

calibration stand. The bottom of the transducer is equipped with a 1/4"-28 thread female socket, into which the vanes are screwed.

When the vane is attached to the transducer, the motor causes the vane to turn in the sample. The resistance provided by the soil to the vane is opposite in direction to the vane rotation. Thus, the motor and the resistance of the soil act in opposite directions, resulting in a twisting moment being applied to the torque transducer. The strain gages attached to the inner shaft of the transducer measure the shaft deflection caused by this twisting moment. The output of the strain gages is linear and directly proportional to the amount of deflection of the shaft.

Power supply and output signals are sent through a four wire conductor equipped with a Viking connector which is plugged into the back of the power supply and signal conditioning unit.

Power Supply and Signal Conditioning Unit

This is a combined transistorized power supply, bridge circuit, and amplifier as is shown in the photograph of Figure 6. The power supply provides 5 volt DC excitation to the strain gages. The output signal from the strain gages produces an imbalance in the bridge circuit proportional to the torque applied to the transducer. This imbalance results in an output which is fed through a variable gain amplifier to the recorder.

The unit is provided with a push button resistive circuit equivalent to a 125 inch-ounce torque (half range load) and may be used to adjust the amplifier gain. When the "R Cal" button on the back panel is depressed, the signal from the strain gages is interrupted and

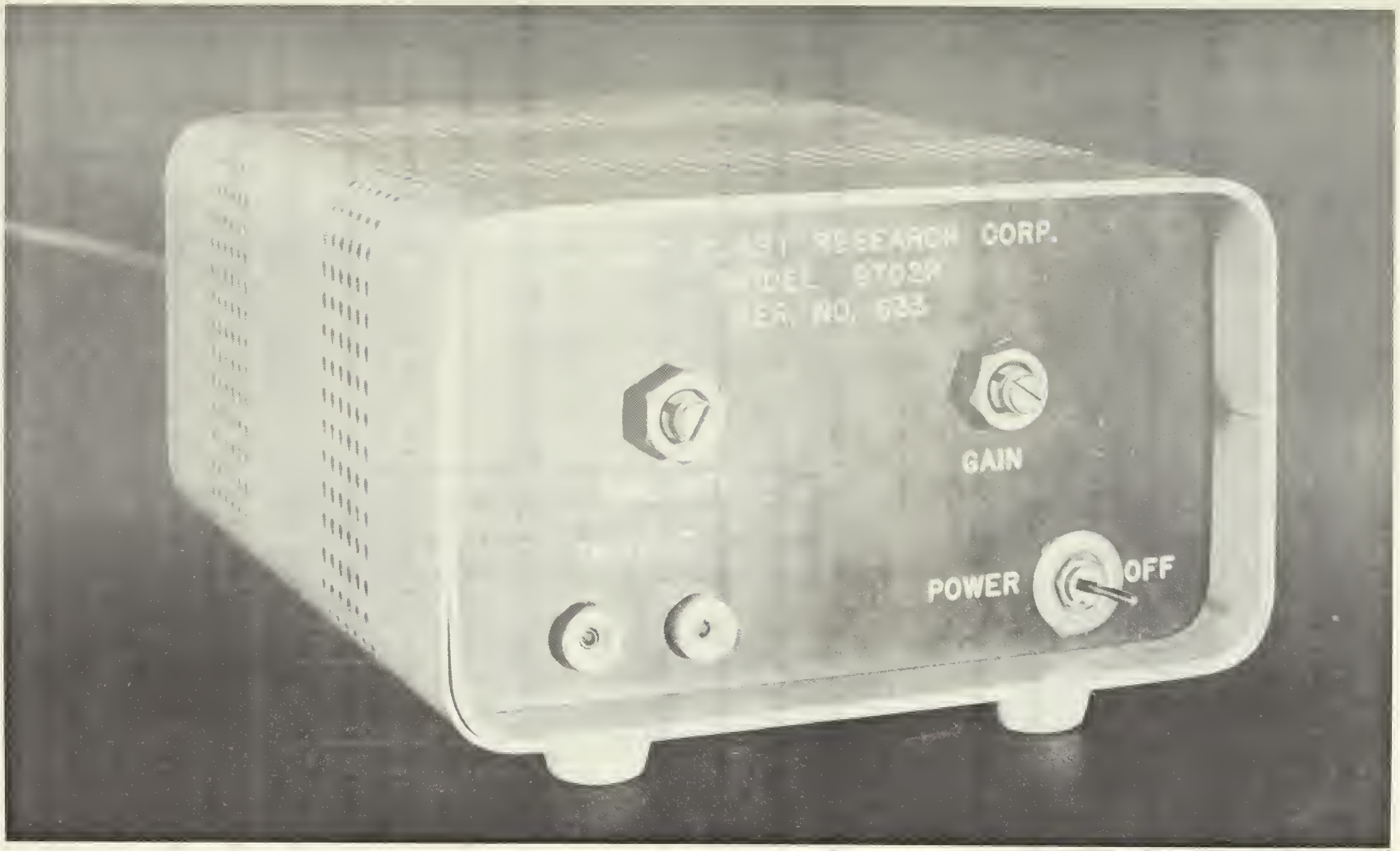

Figure 6. The Power Supply and Signal Conditioning Unit

the electrical equivalent of the 125 inch-ounce torque reading is substituted. In operation, it is recommended that a 1 volt full scale reading be set on the recorder, the "R Cal" button depressed, and the amplifier gain adjusted until the recorder trace reads 0.5 volts. This sets the amplifier at 4 millivolts per inch-ounce torque, a voltage that is easily read on all quality recorders.

The balance knob enables the reference level to be shifted to any desired position, comparable to a "zero adjust" on a recorder.

Recorder

Any quality recorder may be used and several models were utilized during the testing phase with equal success. It is recommended the recorder have a minimum input impedance of 1 megohm, and that it possess a 1 millivolt/division scale on the scale selector.

Bracket Arm

The bracket arm assembly of Figure 7 provides separation of the other components from the vertical shaft. The entire assembly may be moved vertically on the shaft after loosening the arm key. The vanes are usually positioned about 6 inches above the sample and the arm key secured. This provides sufficient space to install and remove the sample during testing. Final lowering or raising of the vanes into the sample is accomplished by the rack and pinion assembly.

The material used in fabrication of the bracket assembly is aluminum, chosen because it is rugged yet light-weight. A two inch brass sleeve, one inch in diameter, is fitted into the end holes. The swivel assembly rotates around the brass sleeve. A set screw is provided on one prong of the bracket assembly to prevent the brass sleeve from rotating with the swivel assembly.

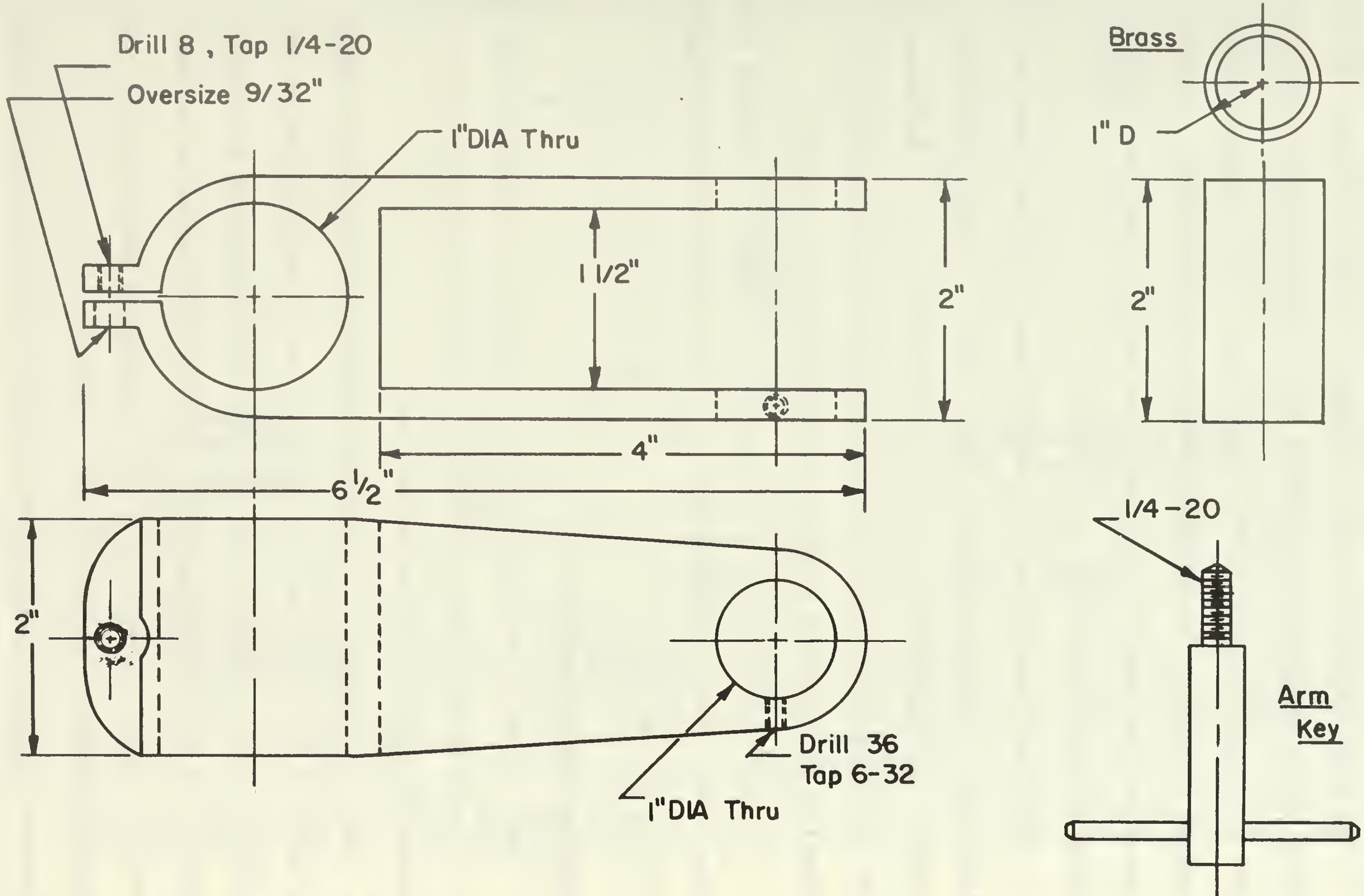

Figure 7. Detail of the Bracket Arm

Swivel Assembly

The swivel assembly, shown in Figure 8, allows the vane, transducer, motor, and rack and pinion assembly to be rotated about a horizontal axis passing through the brass sleeve of the bracket arm assembly. This feature is used in the shipboard configuration when the cores being tested are too long to be placed in the vertical position. Figure 9 shows how this feature may be utilized.

The swivel assembly may be rotated about the brass sleeve by loosening the quarter inch set screw, located on top of the swivel assembly immediately behind the 0.10 inch sawcut slot. Tightening of the set screw decreases the diameter of the hole, which locks the swivel in any position relative to the bracket arm assembly.

The pinion part of the rack and pinion assembly is attached to the front face of the swivel assembly by the 3/8 inch drilled and tapped fitting provided.

Rack and Pinion Assembly

The purpose of the rack and pinion assembly of Figures 10 and 11 is to provide fine scale positioning of the vane without having to change the position of the bracket arm.

The pinion portion is screwed into the front face of the swivel assembly as described above. There are two screws provided on the pinion. The set screw allows the drag between the rack and pinion parts to be adjusted. Tightening the set screw increases the drag, and more torque is required to turn the knurled knob, which in turn moves the rack portion up or down. The set screw should never be loosened completely, as this removes all friction between the parts

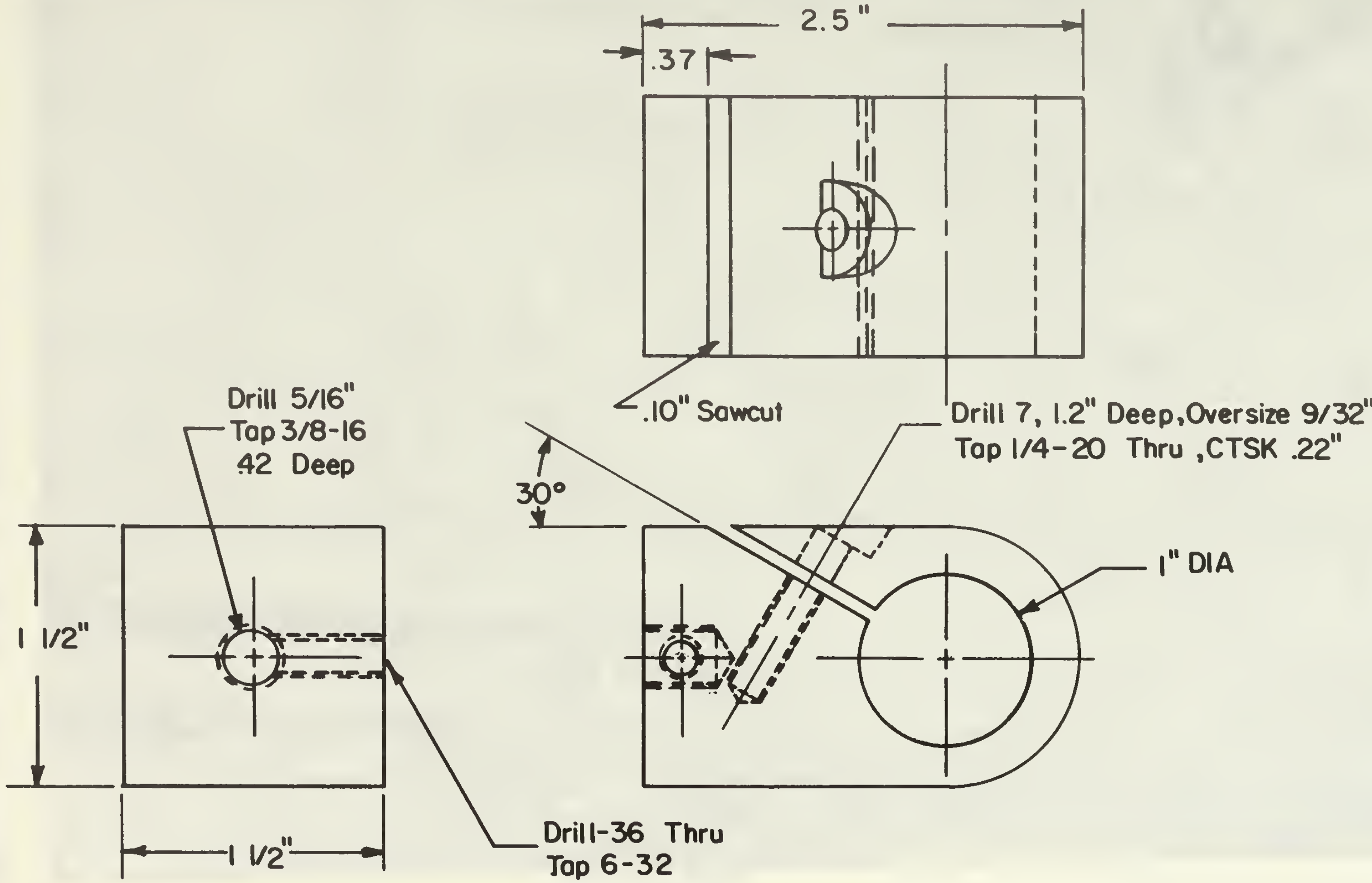

Figure 8. Detail of the Swivel Assembly

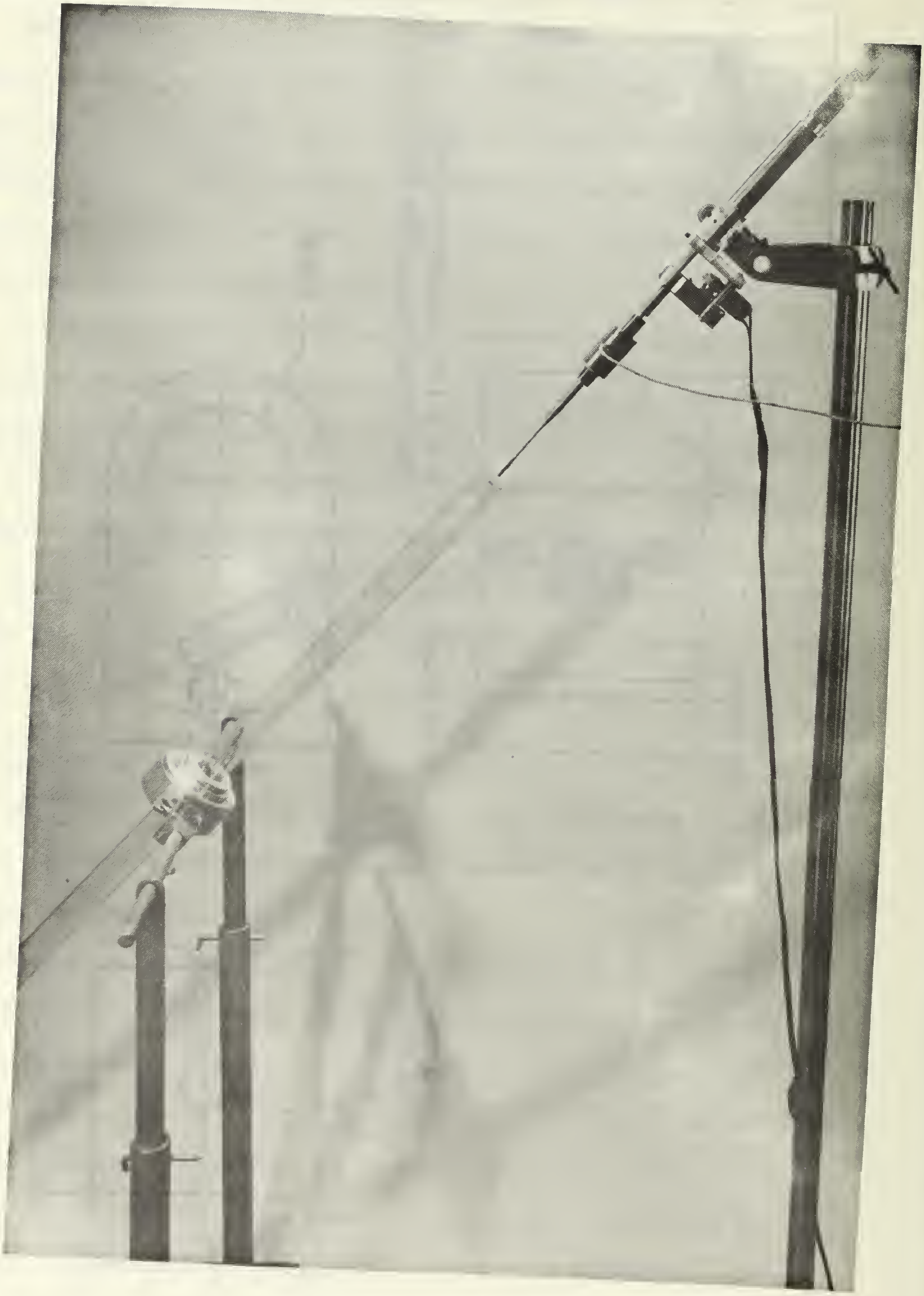

Figure 9. The PGS Vane-Shear Apparatus with Core Holder

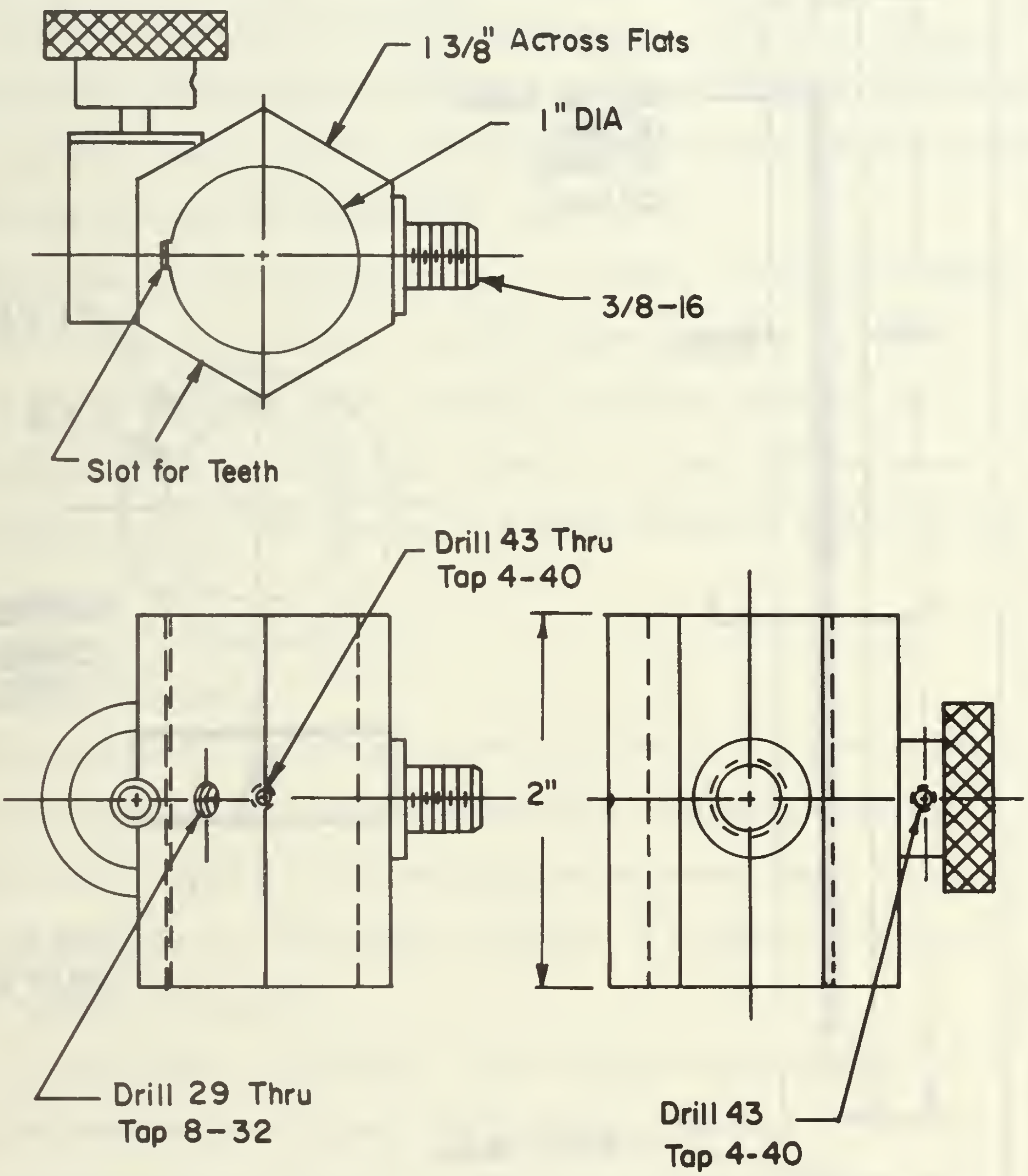

Figure 10. Detail of the Pinion

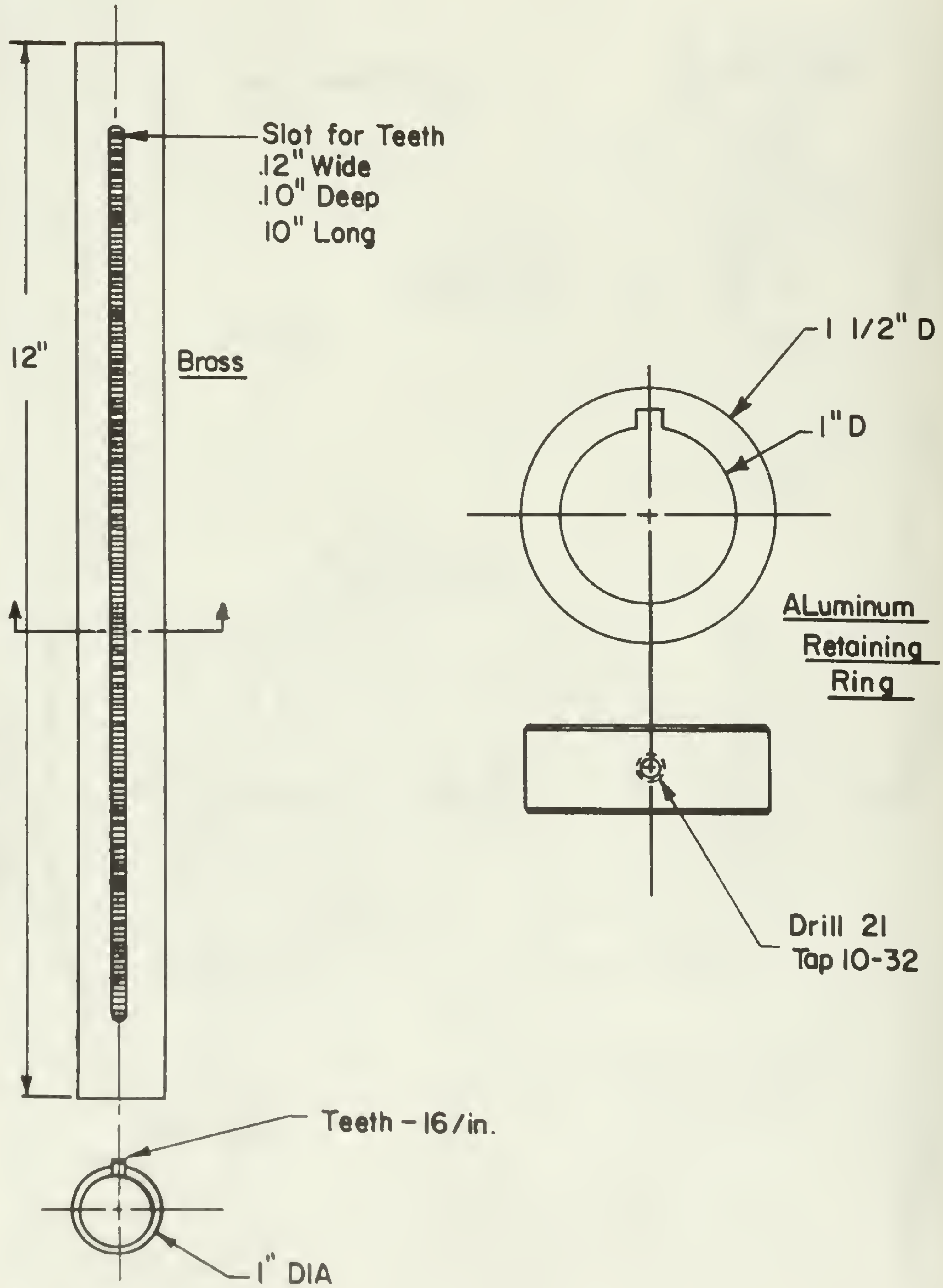

Figure 11. Detail of the Rack

and the rack portion will fall freely by its own weight. The thumb screw on the pinion part of the assembly allows the rack to be locked in place in any position. Both screws are teflon tipped to prevent scoring of the barrel of the rack portion.

An aluminum retaining ring fits over the barrel of the rack portion. The retaining ring is slotted to avoid interference with the gear teeth so that the ring may be positioned at any location.

The purpose of the retaining ring is two-fold: first, it prevents free fall of the rack portion if the set screw adjusting the drag should inadvertently be turned the wrong direction; secondly, the retaining ring may be positioned so that it is flush with the motor mount when the top of the vane is 0.75 inches below the surface of the sample being tested.

Motor and Motor Mount

The motor mount provides the means for securing the motor to the rack protion of the rack and pinion assembly. The mount shown was designed for a specific motor installation and would require alteration if the motor is subsequently replaced. A drawing of the motor mount appears as Figure 12.

The single phase, synchronous, heavy duty motor is manufactured by Hurst Manufacturing Corporation, Princeton, Indiana. It is rated at 150 inch-ounces of torque at 1 RPM and requires 115 VAC, 60 cycle power. The output shaft rotates at one revolution per hour in a counterclockwise direction. The reduction gears are contained in a sealed unit and require no lubrication.

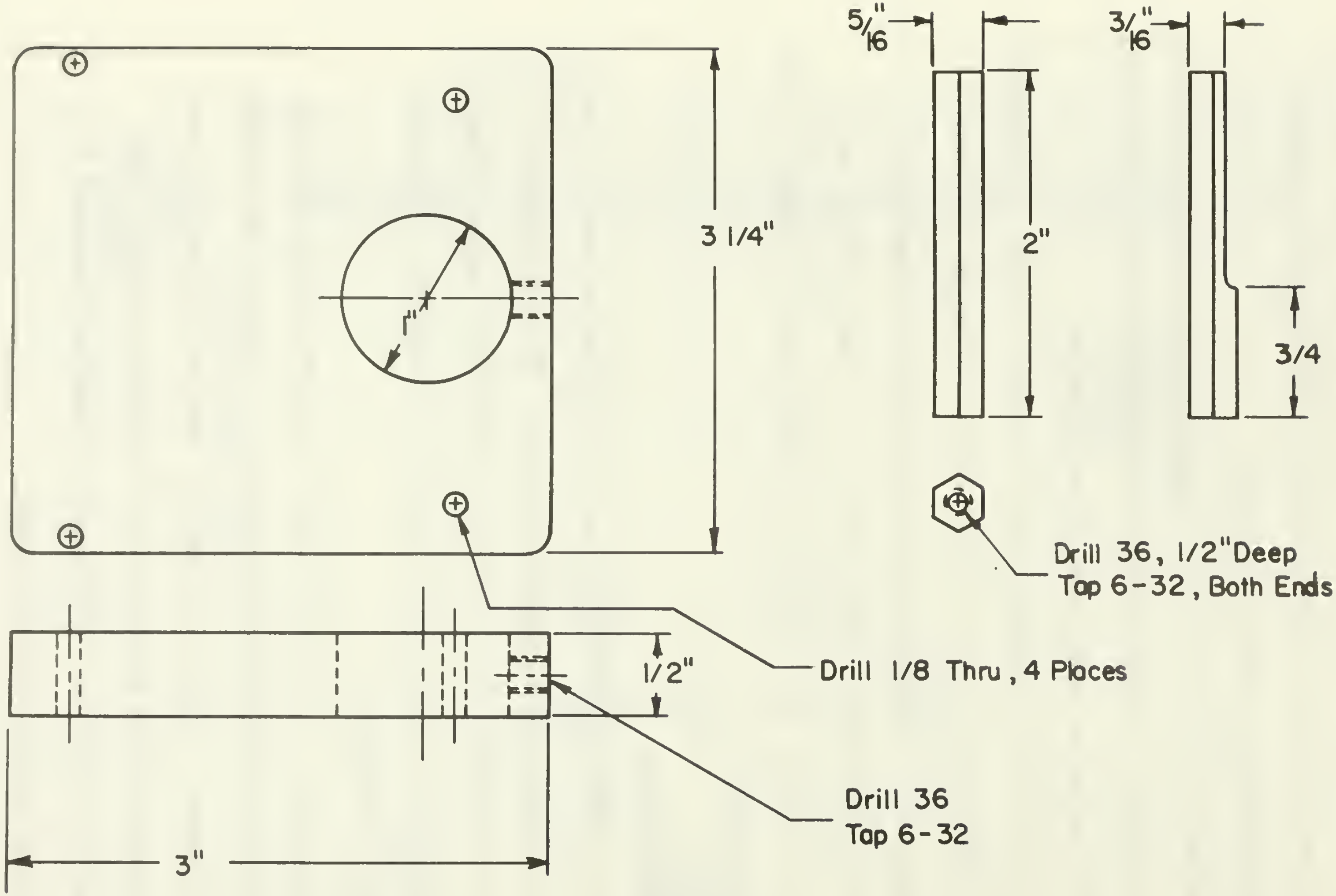

Figure 12. Detail of the Motor Mount

Vanes

Four vanes are provided with the apparatus. The vane dimensions are shown in Figure 13. The entire vane is constructed of stainless steel. The vanes were fabricated independently of the shaft to a tolerance of 0.001 inch, then silver-soldered to the shaft. The top portion of the shaft screws into the base of the transducer.

From the shear strength formula

$$s = \frac{\text{torque}}{\left(\pi DH \frac{D}{2} + 2\pi \frac{D^2}{4} \frac{2}{3} \frac{D}{2}\right)}$$

it can be seen that the denominator in the above equation is a constant for each vane. The constants for each vane provided with the apparatus are as follows:

Vane Dimensions (inches)		
H	D	Constant (in^3)
1/2	1/2	.2616
1	1/2	.4581
1	1	2.0943
2	1	3.6652

To determine shear strength in ounces per square inch, the maximum torque required to shear the soil (inch-ounces) is divided by the appropriate vane factor. The shear strength can then be converted to other, more common units by the appropriate conversion factors. For example, shear strength (lbs/ft^2) = shear strength (oz/in^2) x 9.0.

Calibration Apparatus

After setting the amplifier gain to the desired level, by use of the "R Cal" feature on the signal conditioning unit, the output of the torque

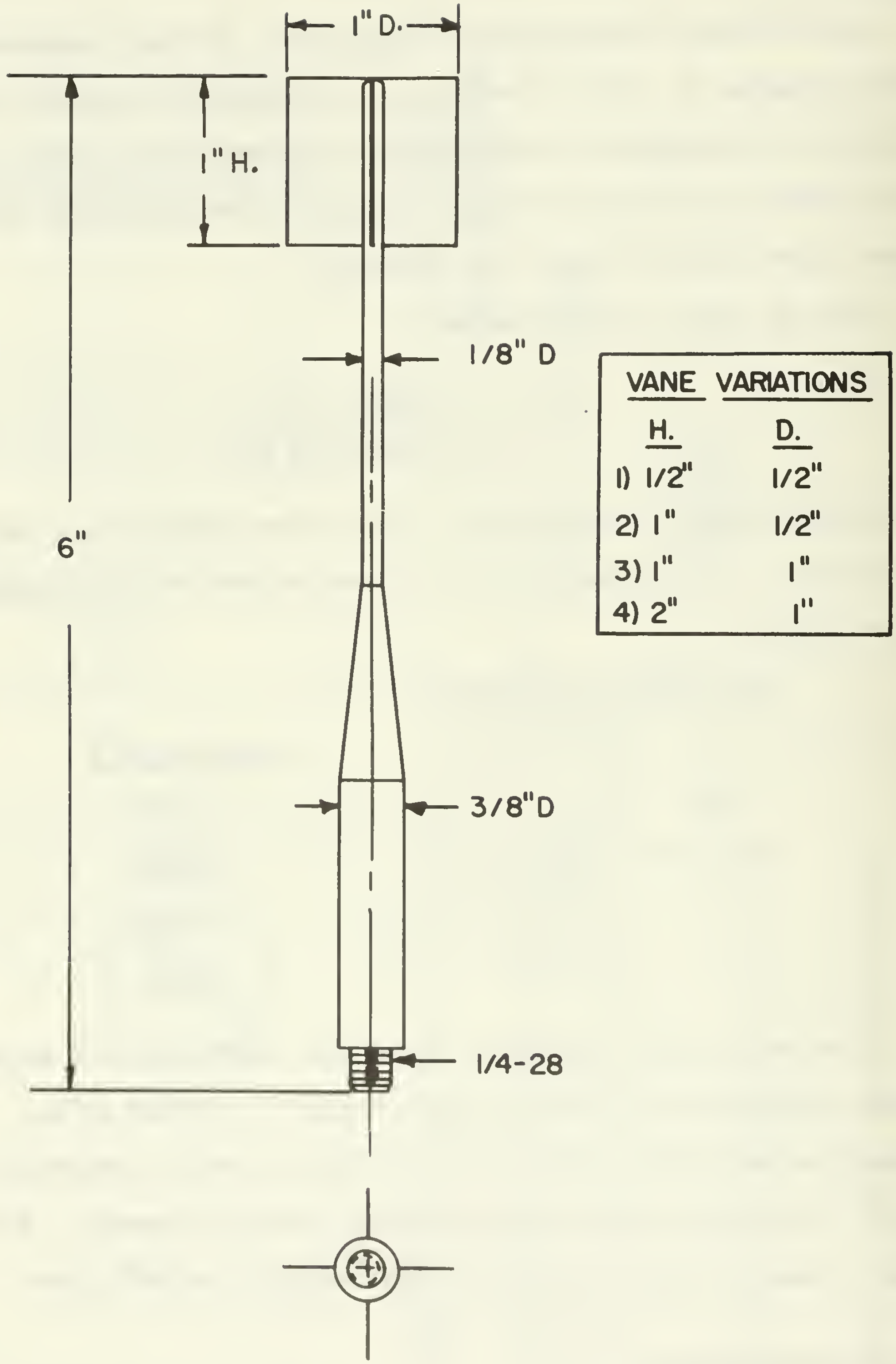

Figure 13. Detail of the Vanes

transducer and amplifier should occasionally be checked against a known torsional moment to ensure that the resistive value of the "R Cal" circuit remains unchanged. This can be accomplished through the use of the calibration apparatus shown in Figures 14, 15, and 16.

The calibration stand, two arms, and the calibration wheel provide the means for applying known torsional moments to the transducer. The torque transducer is screwed into the hole provided in the center of the stand. The calibration wheel is then screwed into the base of the transducer. The wheel has a diameter of 3.0 ± 0.001 inches at the notches. Known weights are attached to the end of a piece of light-weight fishing line. The other end of the line is attached to the notches in the calibration wheel, and the lines passed over the grooved wheels at the top of the guide arms. The wheels in the guide arms are ball-bearing mounted to eliminate friction between the string and the guide wheels. The output signal from the known torsional moment is then read. The reading should correspond to the reading anticipated from known torque, depending on how the amplifier gain is set. For example, if the amplifier gain is adjusted (by means of the "R Cal" feature) to give 4 millivolts per inch-ounce of torque, and each suspended weight is 10 ounces, the total applied is 30 inch-ounces. The output reading from the transducer should then be 120 millivolts.

The calibration procedure described above is not necessary in the course of normal operation. Experience has shown that calibration by the "R Cal" feature of the power supply and signal conditioning unit is very accurate. The calibration apparatus described above should be used only if there is reason to believe the resistive value of the

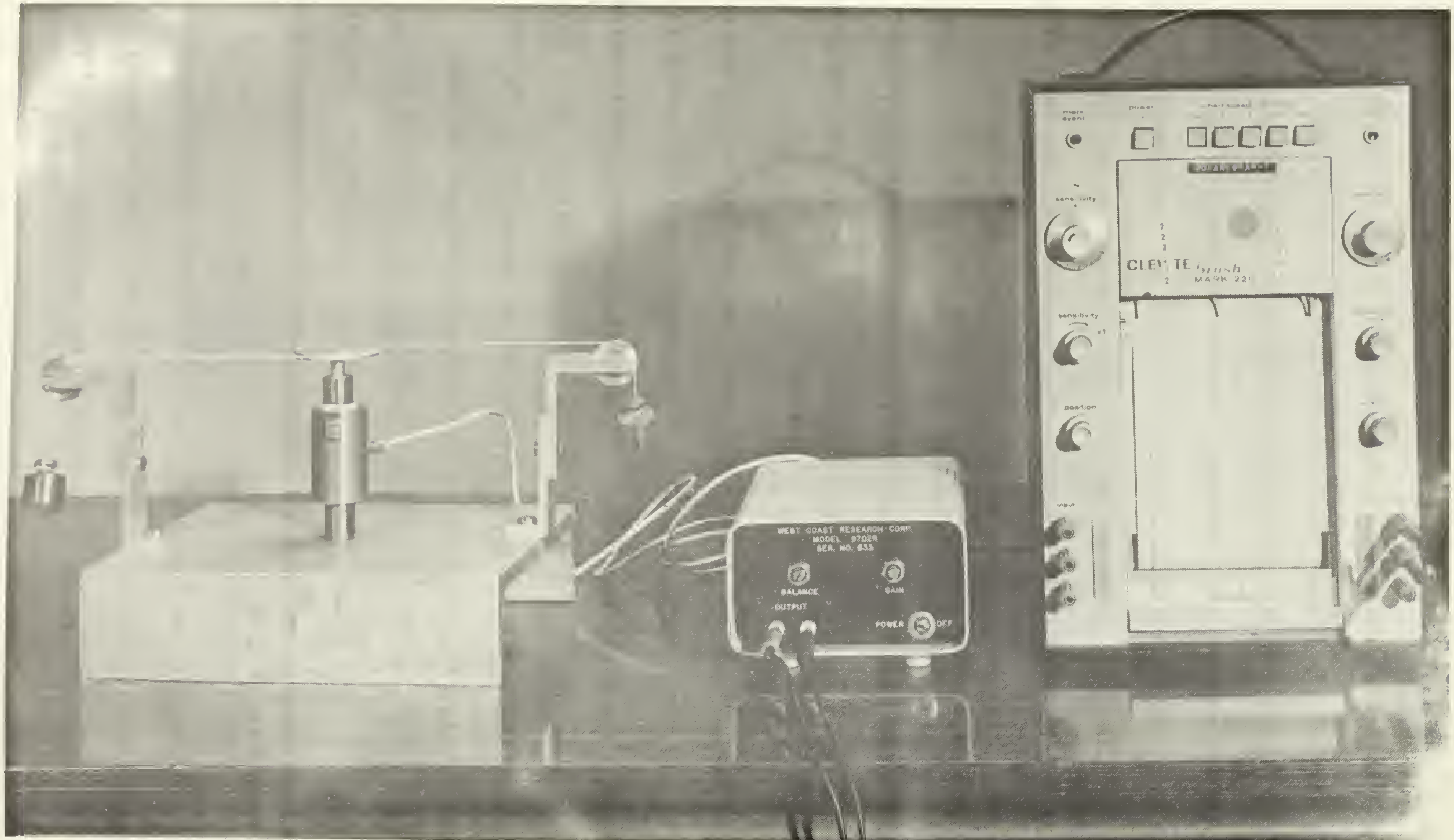

Figure 14. The Calibration Apparatus with Torque Transducer and Calibration Wheel Attached

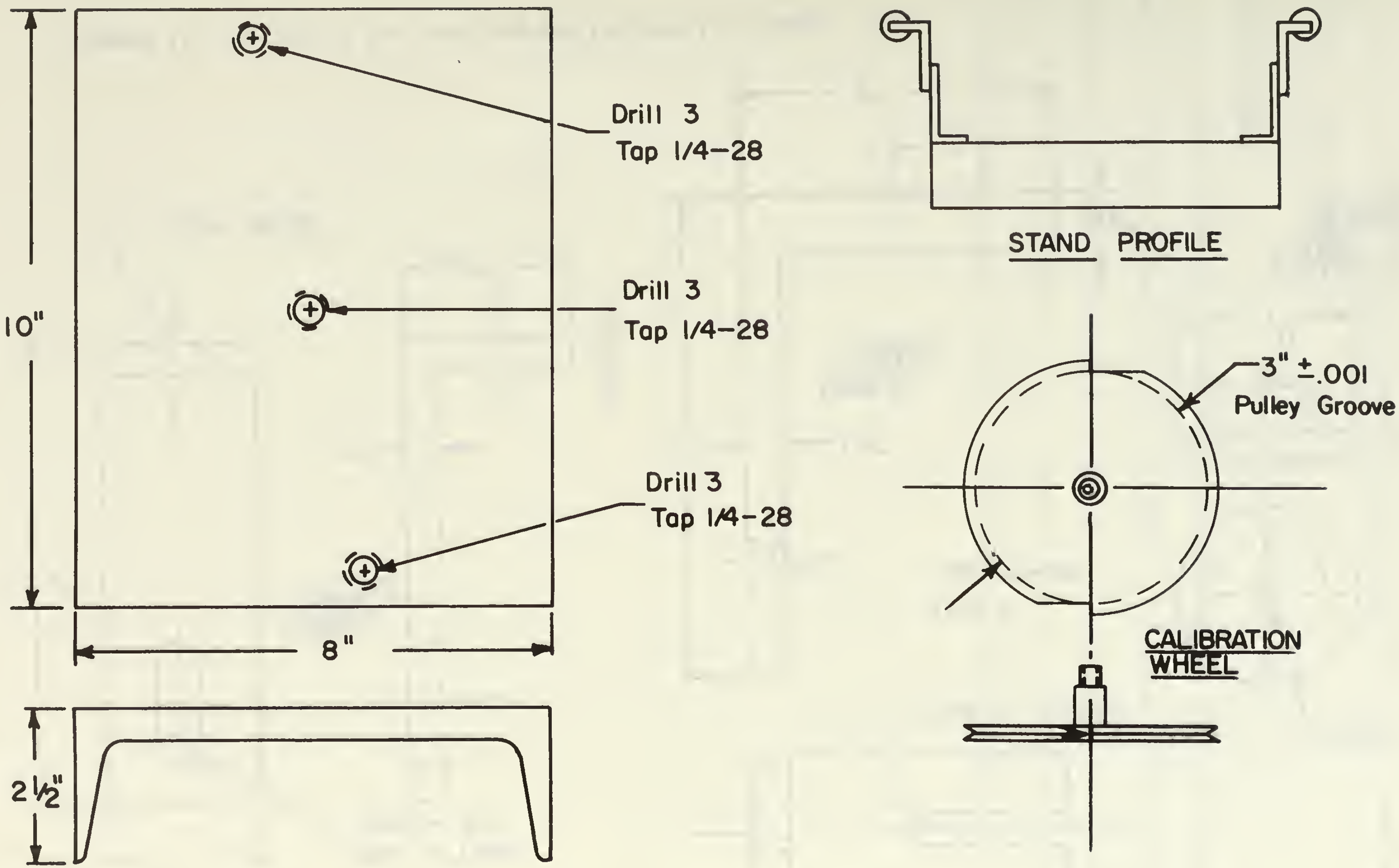

Figure 15. Detail of the Calibration Stand and Wheel

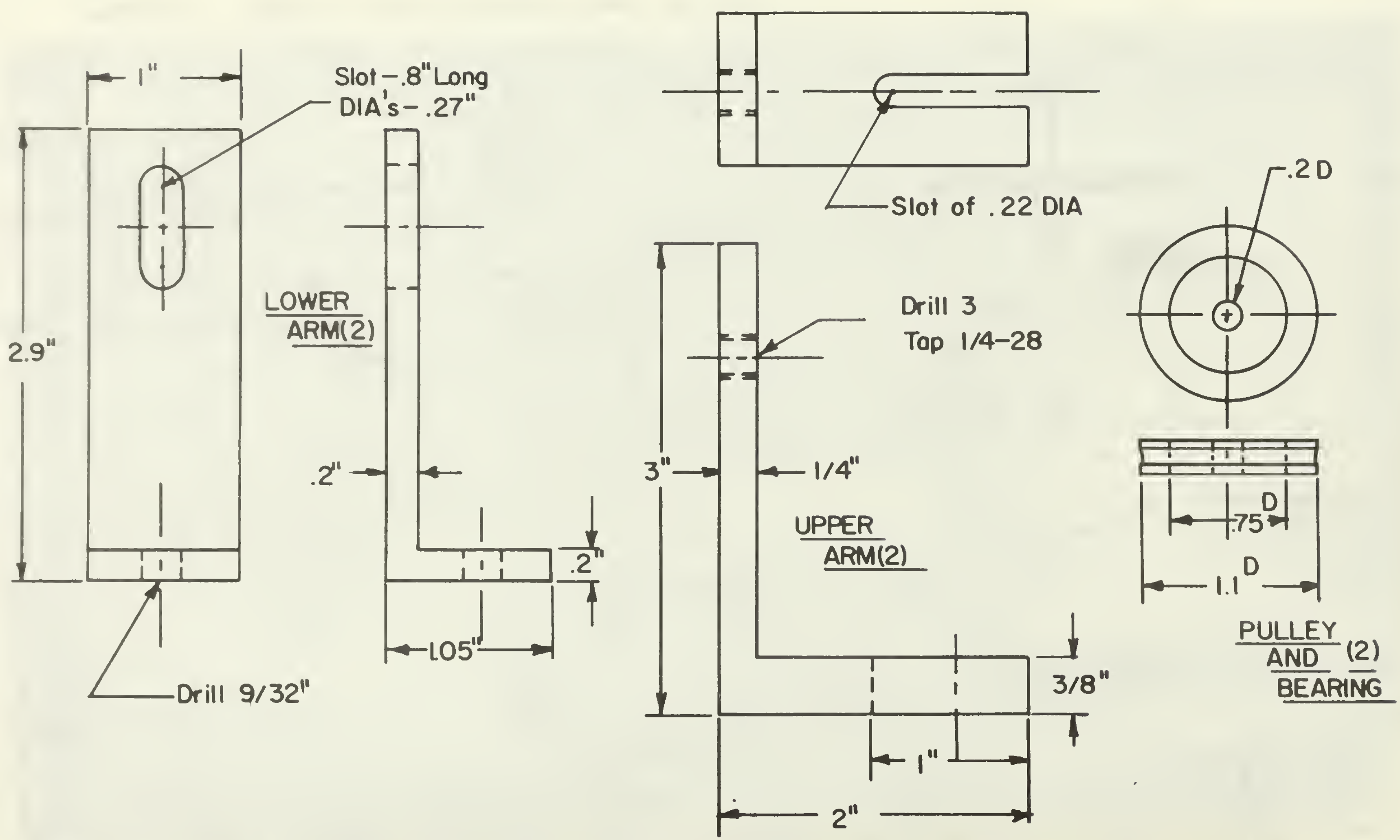

Figure 16. Detail of the Arms for the Calibration Stand

"R Cal" circuit has changed. The calibration apparatus was originally designed to check the output specifications supplied by the manufacturer of the torque transducer.

Core Holders

The legs of the core holders may be adjusted, in three inch increments, to heights between 2.5 and 4.0 feet. The cross member may be rotated to facilitate placing the core at any desired angle. Adapters are provided to accommodate core liners of 3.5, 3.0, 2.5, and 1.5 inches outside diameter. The assembled core holder is shown in Figure 9.

TEST PROCEDURES AND RESULTS

The PGS vane-shear apparatus was transported to the Naval Civil Engineering Laboratory at Port Hueneme, California where provision was made for cores and samples from storage and use of the NCEL vane-shear apparatus permitted in order to establish comparative values from each device. Tests were conducted on numerous samples and the results obtained from each vane-shear apparatus compared. In order to eliminate temporal variability of the samples as much as possible, comparative tests were conducted within fifteen minutes of each other. The apparatus selected to test each sample first was varied randomly so that the succeeding test result would not be biased by the result of the first test.

It was not possible to obtain comparisons of undisturbed shear strength, although several attempts were made to conduct such tests. The maximum length of core which can be tested on the NCEL apparatus is three inches. The sample was first tested on one apparatus, then inverted and tested on the other, but portions of the vane on the second test were extruding into the cylindrical area previously ruptured by the first test. Since it was impossible to extend the length of the test sample (because of the three inch limitation on sample length with the NCEL apparatus) it was necessary to resort to remoulded samples to obtain a valid comparison.

The samples were chiefly dark, clayey sediments containing numerous shell fragments. Where large discrepancies existed in the test results, examination of the sample revealed shell fragments or other irregularities

on or in the vicinity of the shear cylinder. Only those tests which were considered valid are included in the results.

Test Procedure

After cutting the core liner, the soil was extruded from the liner into a ten inch diameter crucible and thoroughly mixed and kneaded. Visible shell fragments and other foreign objects were removed. In certain instances, water was added to the sample to obtain a more favorable consistency in order to ensure valid comparisons over a representative range of strengths. The soil was then placed in a brass cylinder 3 inches long and 2-1/2 inches in diameter. The cylinder was secured to the sample holder and the vanes lowered to 0.75 inches below the surface of the sample. The rotation rate used during all tests was one revolution per hour. Upon completion of the test, the sample was removed and again mixed thoroughly and replaced in the cylinder. The test was then repeated on the second apparatus.

Results

Fifteen valid sets of comparative data were obtained, the results of which are shown in Table III. The right hand column of Table III expresses the value of the NCEL apparatus result as a percentage of the value obtained with the PGS apparatus. The largest difference obtained expressed as a percentage of NCEL ÷ PGS, was 19.7 percent. The smallest difference was 1.2 percent. Of the fifteen comparative values, three had a difference greater than 10 percent, three had a difference between 5 and 10 percent, and nine had a difference of less than 5 percent. The average difference of results for all tests is

TABLE III

Test Results

Sample No.	Shear Strength (lbs/ft^2)		NCEL/PGS - Expressed as a percentage
	NCEL	PGS	
PP-2:			
0-3R	379.8	473.0	80.3
3-6R	214.7	206.3	104.1
0-3R(+$H_2$0)	51.0	49.1	103.9
6-3R(+$H_2$0)	58.95	68.8	85.7
6-10R	101.5	98.2	103.3
13-16R	59.0	66.3	90.0
16-18R	45.8	46.6	98.3
TH-1:			
3-6R	85.95	88.65	97.0
6-9R	53.0	55.9	94.8
12-15R	71.9	61.4	117.1
TH-2:			
0-3R	74.4	69.8	106.6
6-9R	53.0	51.0	103.9
12-15R	35.8	36.5	98.1
TH-3:			
12-15R	150.5	152.3	98.8
12-15R(+$H_2$0)	47.3	48.3	97.9

6.5 percent. If the tests having a difference greater than 10 percent are discarded, the average difference between results decreases to 3.9 percent.

Nine of the fifteen remoulded shear strength values obtained by the PGS device were greater than the value obtained by the NCEL apparatus, which represents 60 percent of the total number of tests. It was anticipated that this percentage would be higher because of suspected frictional losses in the bushing and bearings on the NCEL device, especially at very low torque values. Additional comparisons may show this to be the case.

On 5 February 1970 a core sample was obtained by the Naval Oceanographic Research Ship BARTLETT off the coast of Central California, at latitude 36°30'N, longitude 123°56'W, in a water depth of 4200 meters. The core was cut into three inch sections, and shear strength tests were obtained on each of the sections using the PGS apparatus. The results of these tests are shown in Figure 17, which is a plot of shear strength versus length from the top of the core.

Examination of the core prior to cutting revealed what appeared to be a water pocket approximately one inch long at a length of twenty-one inches from the top of the core. Subsequent cutting of the core showed a difference in color and texture of the sediments above the water pocket from those below. The shear strength values obtained verify the existence of the two distinct sediment types, the upper sediment being much stronger than that below the twenty-one inch level.

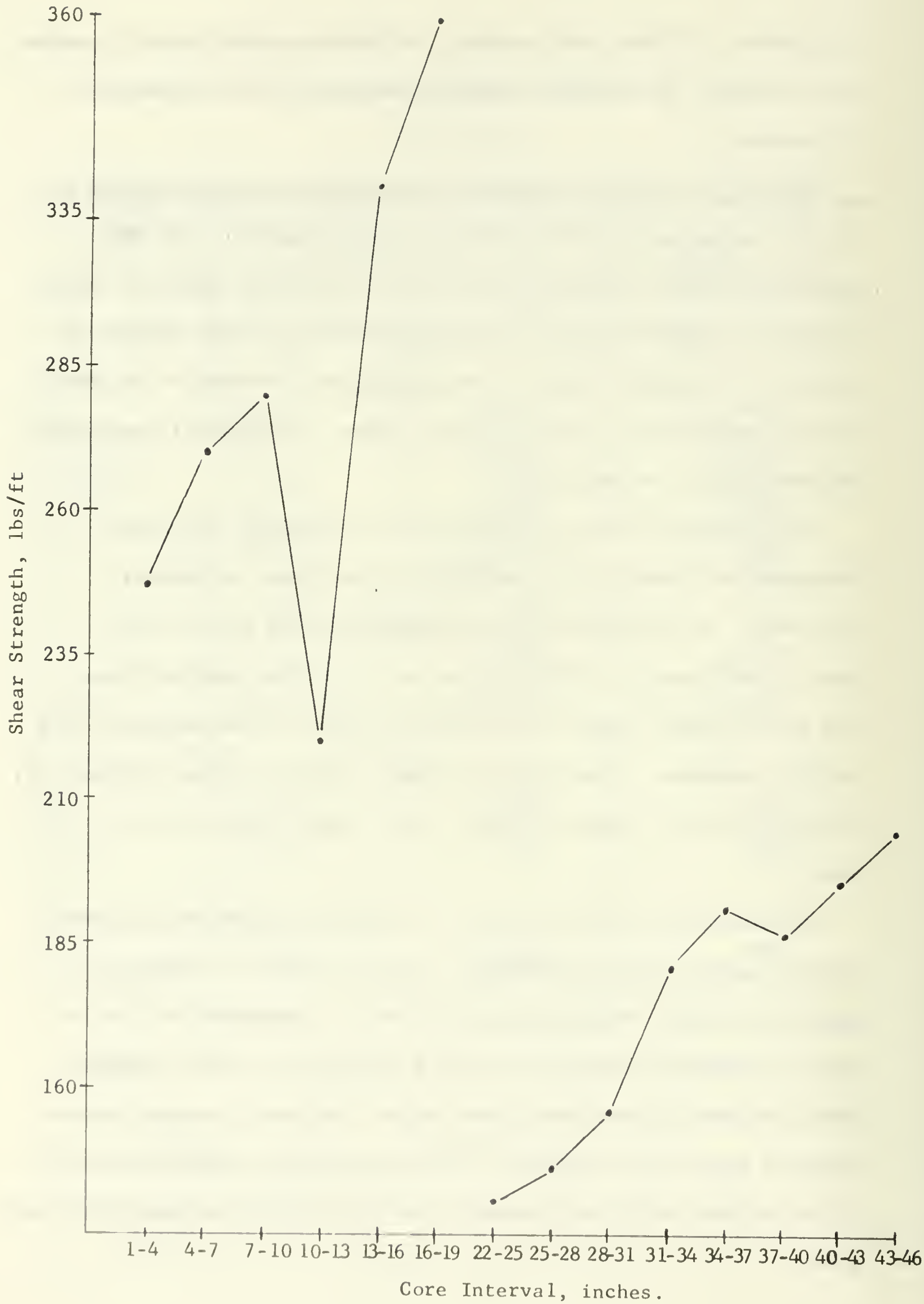

Figure 17. Graph of Shear Strength vs. Length in Core

After determining the shear strength of each core section with the PGS vane-shear apparatus, the sample was inverted after each test and a subsequent shear strength value determined with the Wykeham Farrance vane-shear apparatus. Care was taken to ensure the ruptured areas did not overlap. Table IV shows the results of these comparisons. The largest difference obtained, expressed as a percentage of Wykeham Farrance ÷ PGS, was 10.0 percent. Two samples had a difference between 5.0 and 10.0 percent, and eleven of the fourteen samples had a difference less than 5.0 percent. The average difference of shear strength values obtained by these tests was 3.08 percent.

A total of twenty-nine comparative tests were obtained; fifteen with the NCEL vane-shear apparatus, and fourteen with the Wykeham Farrance vane-shear apparatus. The average difference of all twenty-nine tests is 4.86 percent. If the three tests showing a difference of greater than 10.0 percent (which may be attributed to handling, testing procedures, etc.) are discarded, the average difference of the remaining twenty-six tests is 3.6 percent. This average is considered reasonable for this type of test, since handling, cutting of core liners, and other factors can produce significant differences in test results.

The data comparing the PGS vane-shear apparatus with the NCEL and Wykeham Farrance devices was subjected to a statistical analysis by the use of the Paired Student-t Test. The objective of this analysis was to determine if there is any significant difference between the results obtained with the PGS apparatus and the results obtained with the NCEL and the Wykeham Farrance devices. Tables V and VI show the results of these tests. In both cases, the null hypothesis is that

TABLE IV

Additional Test Results

Sample number	Shear Strength (lbs/ft^2)		W.F./PGS Expressed as a percentage
	PGS	Wykeham Farrance	
OPG-9:			
1-4	272	266	97.7
4-7	294	288	98.0
7-10	304	286	94.2
10-13	245	235	96.0
13-16	341	343	100.5
16-19	359	352	98.0
12-22 No test because of water pocket			
22-25	166	182	109.5
25-28	172	190	110.0
28-31	181	181	100.0
31-34	206	204	99.0
34-37	216	214	99.0
37-40	211	209	99.0
40-43	220	217	98.5
43-46	228	222	97.5

TABLE V

Paired Student-t Test Results, PGS vs. NCEL Data

Sample Number	Shear Strength (lbs/ft^2)		Difference (X_d)	$(X_d - \bar{X}_d)^2$
	PGS	NCEL		
PP-2:				
0-3R	473.0	379.8	93.2	7607.3
3-6R	206.3	214.7	-8.4	206.7
0-3R (+H_2O)	49.1	51.0	-1.9	62.1
3-6R (+H_2O)	68.8	58.9	9.8	14.6
6-10R	98.2	101.5	-3.3	86.1
13-16R	66.3	59.0	7.3	1.7
16-18R	46.6	45.8	0.8	26.8
TH-1:				
3-6R	88.6	85.9	2.7	10.8
6-9R	55.9	53.0	2.9	19.3
12-15R	61.4	71.9	-10.5	271.6
TH-2:				
0-3R	69.8	74.4	-4.6	111.9
6-9R	51.0	53.0	-2.0	63.7
12-15R	36.5	35.8	0.7	27.9
TH-3:				
12-15R	152.3	150.5	1.8	17.5
12-15R (+H_2O)	48.3	47.3	1.0	24.8
			89.8	8552.8

$$\bar{X}_d = \frac{\Sigma X_d}{N} = \frac{89.8}{15} = 5.98$$

$$s_d^2 = \frac{(X_d - \bar{X}_d)^2}{(N-1)} = \frac{8552.8}{14} = 610.9$$

$$s_d = \sqrt{s_d^2} = 24.7$$

$$t = \frac{\bar{X}_d}{s_d} = \frac{5.98}{24.71} = .24$$

t value for 95% confidence level, 14 degree of freedom = 1.761 [Natrella, 1963].

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$$s_d = \sqrt{s_d^2} = 24.7$$

$$t = \frac{\bar{X}_d}{s_d} = \frac{5.98}{24.71} = .24$$

t value for 95% confidence level, 14 degrees of freedom = 1.761 [Natrella, 1963].

on the average there is no significant difference between the results obtained with the PGS vane-shear apparatus and the device it is compared against. The results of these calculations show that, in both cases, the null hypothesis cannot be rejected since the t-values determined from the test results are less than the tabulated t-values for a 95 percent confidence level. Thus, it is safe to conclude that based on a 95 percent confidence level there is no significant difference between the shear strength values obtained with the PGS apparatus and those obtained with the other two devices.

Recommendations for Further Research

The following areas associated with vane-shear testing are suggested for additional research:

1. Determine the effects of additional blades on the vane. Such additions should result in a shear surface more nearly cylindrical, but may give erroneous results because of additional disturbance and increased pore water pressures.

2. Quantitatively determine the effects of higher vane rotation rates.

3. Investigate the effects of friction exerted by the sediment on the vane shaft.

4. Develop a new technique for cutting all types of core liner material without increasing the disturbance of the sediment. The "hot wire" technique is extremely time consuming with some types of plastic.

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13. ABSTRACT

The vane-shear devices currently in use exhibit inherent problems and shortcomings associated with their design. The PGS Vane-Shear Apparatus is designed to eliminate these shortcomings. The unique features of the device include:

a. Ability to be used in the laboratory or on board ship.

b. A single unit which is easily calibrated and capable of measuring torque over the entire range commonly encountered in marine sediments.

c. A torque transducer which is insensitive to temperature changes and orientation.

d. Ability to determine shear strength prior to cutting the core liner, thus reducing the disturbance to the sediment caused by cutting and handling.

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	ROLE	WT	ROLE	WT	ROLE	WT
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Shear strength						
Marine sediments						
Sediment testing						

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